



## Paleocene orthophragminids from the Lakadong Limestone, Mawmluh Quarry section, Meghalaya (Shillong, NE India): implications for the regional geology and paleobiogeography

Ercan Özcan<sup>1</sup>, Johannes Pignatti<sup>2</sup>, Christer Pereira<sup>3</sup>, Ali Osman Yücel<sup>1</sup>, Katica Drobne<sup>4</sup>,  
Filippo Barattolo<sup>5</sup>, and Pratul Kumar Saraswati<sup>3</sup>

<sup>1</sup>Department of Geological Engineering, Faculty of Mines, İstanbul Technical University (İTÜ), Maslak, 34469 İstanbul, Turkey

<sup>2</sup>Dipartimento di Scienze della Terra, Università degli Studi di Roma “La Sapienza”, Rome, Italy

<sup>3</sup>Department of Earth Sciences, Indian Institute of Technology, Bombay, Powai, Mumbai 400 076, India

<sup>4</sup>Palaeontological Institute I. Rakovec ZRC SAZU, Novi trg 2, 1000 Ljubljana, Slovenia

<sup>5</sup>Dipartimento di Scienze della Terra, dell’Ambiente e delle Risorse  
Largo San Marcellino, 10, 80138 Naples, Italy

**Correspondence:** Ercan Özcan (ozcanerc@itu.edu.tr)

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**Abstract.** The late Paleocene orthophragminids, hitherto poorly known from the Himalayan foreland basins, are studied from the Lakadong Limestone in Meghalaya, northeastern India, in order to establish a systematic, biostratigraphic, and paleobiogeographical framework for them in the eastern Tethys. In the Mawmluh Quarry section (MQS) on the Shillong Plateau, to the southeast of Tibet, orthophragminids are associated with typical Paleocene orbitoidiform taxa endemic to the Indian subcontinent, i.e., *Lakadongia* Matsumaru & Jauhri (= *Setia* Ferrández-Cañadell) and *Orbitosiphon* Rao, and various species of alveolinids, miscellaneids, and rotaliids, characterizing the Shallow Benthic Zones (SBZ) 3 and 4. The orthophragminids belong to two lineages of the genus *Orbitoclypeus* Silvestri: *O. schopeni* (Checchia-Rispoli) and *O. multiplicatus* (Gümbel), both well known from the peri-Mediterranean region and Europe (western Tethys). The latter species is identified here for the first time from the eastern Tethys. Previous records of the genus *Discocyclina* Gümbel from the Lakadong Limestone actually correspond to misidentified *Orbitoclypeus*; this implies that the late Paleocene orthophragminid assemblages from Meghalaya and eastern Tethys were less diverse than in the western Tethys. The lineage of *Orbitoclypeus schopeni* in the lower part of the Lakadong Limestone (SBZ 3) is identified as *O. schopeni* cf. *ramaraoui* based on the morphometry of a few specimens, whereas in the upper part (SBZ 4) it corresponds to a transitional development stage between *O. schopeni ramaraoui* and *O. schopeni neumannae* (with average  $D_{\text{mean}}$  values ranging between 192 and 199  $\mu\text{m}$ ). The embryo diameters of *O. multiplicatus*, recorded only in SBZ 4, range between 300 and 319  $\mu\text{m}$  on average, corresponding to transitional development stages of *O. multiplicatus haymanaensis* and *O. multiplicatus multiplicatus*. Our data, along with a review of previous Paleocene and Eocene records from India and Pakistan, suggest that *Orbitoclypeus* is the only orthophragminid in the Paleocene of the eastern Tethys, whereas *Discocyclina* first appears in early Eocene times, being mainly represented by endemic taxa confined to the Indian subcontinent. Facies change in the MQS from a marine to continental setting within SBZ 4 corresponds to the oldest record from the Indian plate in the Paleogene, which may be linked to the flexural uplift of the passive margin of the Indian plate, marking the onset of the collision of the Indian and Eurasian plates.

## 1 Introduction

Orthophragminids are a group of larger benthic foraminifera (LBF) that inhabited the upper Paleocene–Eocene circum-tropical continental shelves and platforms around the globe (Less, 1987). Despite their widespread distribution and a reasonably high number of evolutionary lineages established from the peri-Mediterranean region (western Tethys), a Tethyan-scale biostratigraphic model and a paleobiogeographical scheme have not yet been established because of lack of data from the eastern Tethys (Wan, 1991; Wan et al., 2010; Zhang et al., 2013; Özcan et al., 2014; BouDagher-Fadel and Price, 2017). In the peri-Mediterranean region and Europe, both *Discocyclina* Gümbel and *Orbitoclypeus* Silvestri appear simultaneously in the Thanetian and orthophragminids become more diverse with the first appearance of *Nemkovella* Less and *Asterocyclina* Gümbel after the Paleocene–Eocene boundary (Less et al., 2007; Özcan et al., 2014). The main records of Paleocene orthophragminids from the eastern Tethys come from the Lakadong Limestone in Meghalaya, where a detailed taxonomic study of the group has until now not been available. The occurrence of two orthophragminid genera, *Discocyclina* Gümbel and *Orbitoclypeus* Silvestri, has been reported in previous works from this unit from random thin sections; *Discocyclina* was not identified at the species level, whereas the only orbitoclypeid recorded was *Orbitoclypeus ramaraoi* (*O. schopeni ramaraoi*) (Jauhri, 1994, 1998; Matsumaru and Sarma, 2010). In India, south of the Tethyan domain, Paleocene orthophragminids have been recorded in some detail only from the Cauvery Basin (Pondicherry area) in SE India (Samanta, 1967). Here, orthophragminids are represented only by *Orbitoclypeus schopeni ramaraoi* (*Discocyclina ramaraoi* of Samanta, 1967), the most primitive member of the *O. schopeni* lineage of Less et al. (2007). Other records of Paleocene orthophragminids from the eastern Tethys, e.g., the Andaman Islands (Koley and Wanjarwadkar, 2013), and the southern margin of the Asian plate (Zhongba area, Tibet) (BouDagher-Fadel et al., 2015), are based on poorly preserved or indeterminable uncentered sections.

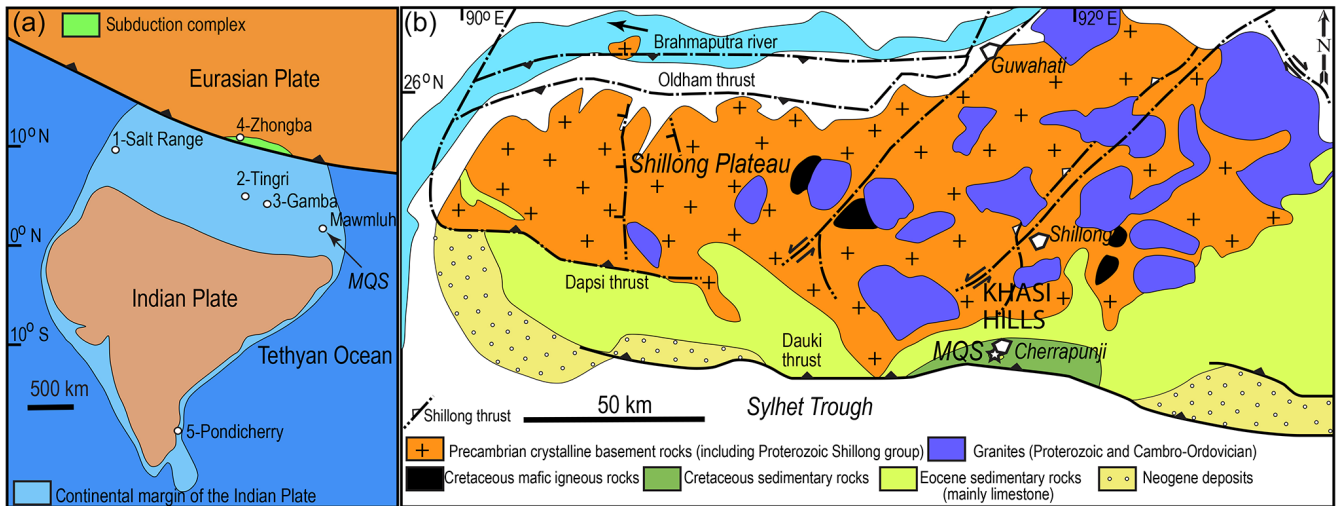
Here, our aim is to fill the gap in information on the eastern Tethyan Paleocene orthophragminids based on the new data from the Lakadong Limestone in Meghalaya. Matrix-free orthophragminid tests were extracted from marly and silty levels to make equatorial sections in order to investigate the embryon and equatorial chambers and obtain the morphometric parameters necessary for subspecies identification. In addition to equatorial sections, axial and subaxial sections of megalospheric forms are illustrated in order to facilitate generic and specific recognition in rock thin sections. The distribution of Tethyan Paleocene orthophragminids is reinterpreted in light of the new data.

## 2 Geological setting and stratigraphy

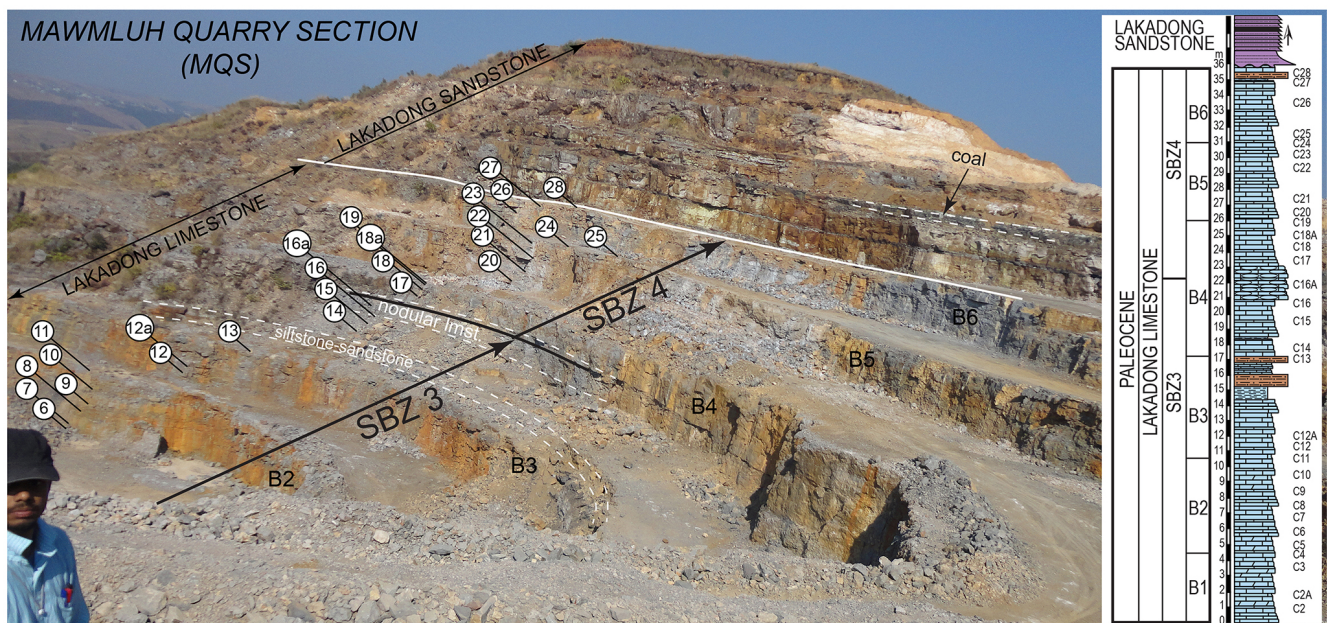
The Shillong Plateau in NE India consists of a Precambrian basement and is covered by Cretaceous and Cenozoic sedimentary deposits in the south, which form a raised topography in the foreland of the Himalayas (Fig. 1) (Biswas et al., 2007; Najman et al., 2016). The southern fringes of the Shillong Plateau, commonly referred to as the southern Shillong Plateau, form the Khasi–Jaintia Hills. The Paleogene succession exposed in the southern Shillong Plateau is represented by the Paleocene fluvio-deltaic Langpar and Therria formations, consisting of fine calcareous shales with occasional limestone bands and a thick sandstone succession, and the overlying Sylhet Limestone Group subdivided into several units: the Lakadong, Umlatdoh, and Prang formations intercalated with two mainly sandstone units (Lakadong Sandstone and Narpuh Sandstone) (Wilson and Metre, 1953). These units are interpreted to record three marine transgressions in the late Paleocene, the early Eocene, and the middle Eocene and are overlain by the upper Eocene Kopili Formation (Jauhri, 1994, 1998). The Lakadong Formation consists of the Lakadong Limestone Member, comprising shallow marine algal–foraminiferal facies, extensively developed in the Khasi and Jaintia Hills, and the Lakadong Sandstone Member, a sandstone–shale unit with coal seams (Jauhri, 1994; Garg and Khawaja-Ateequzaman, 2000; Srivastava and Prasad, 2015). In the Lakadong Formation, LBF occur only in the Lakadong Limestone Member and this unit has been extensively studied for red algae and LBF (Jauhri, 1994, 1998; Jauhri and Agarwal, 2001; Matsumaru and Jauhri, 2003; Jauhri et al., 2006; Gogoi et al., 2009; Tewari et al., 2010; Matsumaru and Sarma, 2010). The age of the unit has been reported either as late Paleocene or to range from the late Paleocene to the early Eocene at different outcrops in Meghalaya based on LBF, most commonly alveolinids and miscellaneids. The unit contains diverse assemblages, including miscellaneids, alveolinids, rotaliids, orthophragminids, textulariids, miliolids, encrusting foraminifera, coralline and dasycladalean algae, gastropods, echinoids, bivalves, and scarce coral fragments.

## 3 Materials and methods

The Lakadong Limestone was logged in the Mawmluh Quarry section (MQS), located near the Mawmluh cement factory, ca. 2.5 km southwest of Cherrapunji on the southern Shillong Plateau (base of the section: 25°15′26.72″ N, 91°42′47.01″ E; top of the section: 25°15′23.39″ N, 91°42′52.03″ E) (Fig. 1). Here, the outcropping succession is about 36 m thick and consists of dolomite, dolomitic limestone, limestone with intervening levels of shale, siltstone, and sandstone (Fig. 2). Although the bottom of the section is largely obliterated by alluvium, nearby ex-



**Figure 1.** (a) Tentative location of the Mawmluh Quarry section (MQS) on Thanetian (ca. 59–56 Ma) paleogeographic cartoon after Hu et al. (2016). Locations of key upper Paleocene shallow-marine sections with LBF in eastern Tethys (1–4) and SE India (5) are shown. (b) Geological map of the Shillong Plateau (simplified from Yin et al., 2010). Pondicherry is the type locality of *Orbitoclypeus schopeni ramaraoi*, the most primitive subspecies of the *Orbitoclypeus schopeni* lineage (Samanta, 1967; Less, 1987).

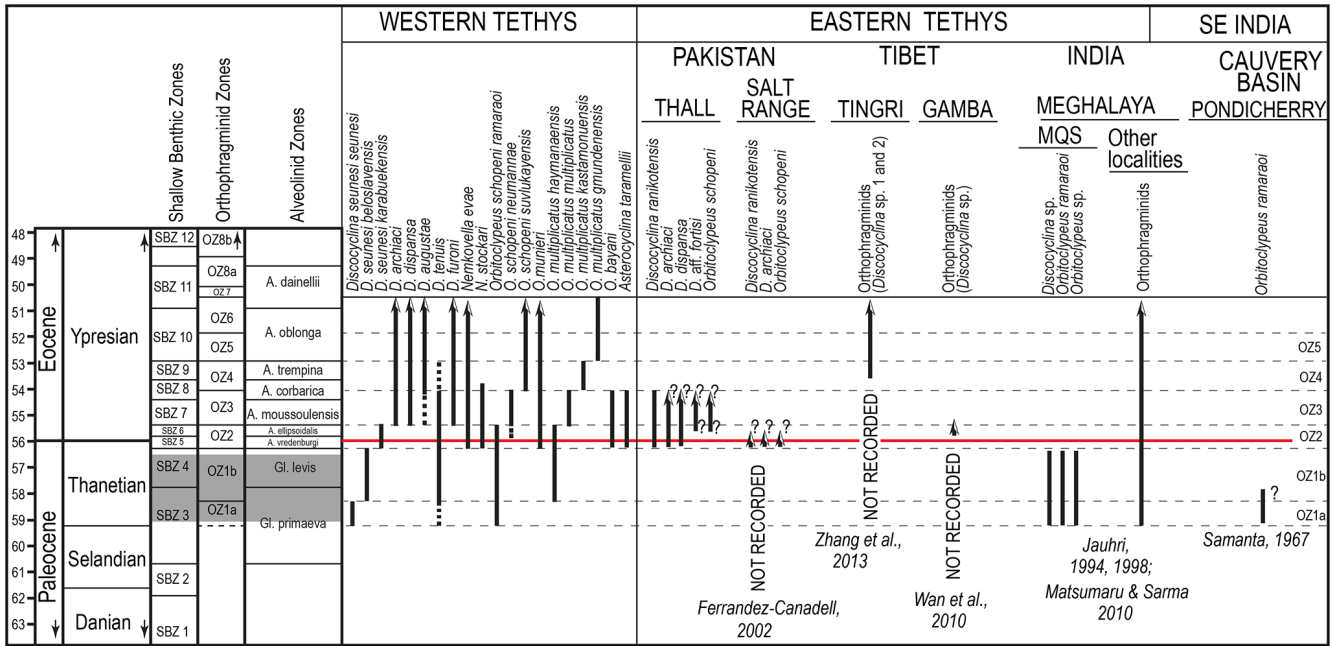


**Figure 2.** The Lakadong Limestone in MQS, position of the samples and simplified stratigraphic column of the quarry. The position of the boundary between SBZ 3 and 4 is tentative. The position of the lower samples (C1–5) from the first bench (B1), are not seen here. B: benches in the limestone.

posures of the unit reveal that in the MQS the exposed lower part of the Lakadong Limestone is very close to the contact with the underlying Therria Formation.

A total of 31 samples from the indurated limestone–dolomitic limestone, and some loose orthophragminid specimens from levels C5, 9, 24, 25, 27, and 28, were collected (Fig. 2). Specimens extracted from the shale, marl, and lime-

stone beds were studied for their external and internal features in equatorial and axial sections. Oriented equatorial sections of megalospheric and partly microspherical specimens (A and B forms, respectively) were prepared because the most important taxonomic and evolutionary parameters are observed in this part of the test (Less, 1987; Ferrández-Cañadell, 1998). Biometric measurements and counts were



**Figure 3.** Records of orthophragminids in the Paleocene and across the Paleocene–Eocene boundary in Tethys and SE India. The Shallow Benthic Zones (SBZ) are after Serra-Kiel et al. (1998), modified by Drobne et al. (2014) and Papazzoni et al. (2017) with respect to the Paleocene–Eocene boundary. The orthophragminid zones (OZ) are from Less et al. (2007) and their boundaries with respect to SBZ zones are after Papazzoni et al. (2017). The alveolinid zones are after Hottinger (1960) and Drobne (1977).

carried out on equatorial sections of the megalospheric specimens (Less, 1987, 1998). Finally, axial and subaxial sections of megalospheric forms were prepared and photographed in order to facilitate specific recognition in rock thin sections.

#### 4 A historical background for Tethyan Paleocene orthophragminids

The late Paleocene phylogeny of Tethyan orthophragminids was reconstructed from localities in Europe and the peri-Mediterranean region, a part of the western Tethyan bioprovince (Schlumberger, 1903; Douvillé, 1922; Neumann, 1958; Samuel et al., 1972; Less, 1987; Zakrevskaya, 2007; Less et al., 2007; Özcan et al., 2014), whereas a systematic study from the eastern Tethys is lacking. In the western Tethys, Paleocene orthophragminids are represented by several species (lineages) of *Discocyclina* Gümbel and *Orbitoclypeus* Silvestri, enabling us to characterize the Thanetian by two orthophragminid zones (OZ), 1a, b and a part of OZ 2 crossing the Paleocene–Eocene boundary (Less et al., 2007). These zones correspond to the Tethyan Shallow Benthic Zones (SBZ) 3, 4, and in part 5 (sensu Papazzoni et al., 2017) (Fig. 3).

The Paleocene orthophragminids from eastern Tethys, however, are little known either because of the absence of the group in some Paleocene key outcrops in Tibet and Pakistan or because of the difficulty in obtaining free specimens

for detailed taxonomic study as in the case of MQS. The Paleocene deposits in Pakistan (e.g., the Lockhart Limestone in the Salt Range) and the Tethyan Himalayas (e.g., the Zhepure Shan and Zongpu formations in Tingri and Gamba regions in Tibet, China) did not yield orthophragminids but only orbitoidiform foraminifers such as *Orbitosiphon* Rao and *Lakadongia* Matsumaru and Jauhri (= *Setia* Ferràndez-Cañadell, see below), in addition to other LBF (Nagappa, 1959; Hu et al., 1976; Wan, 1991; Ferràndez-Cañadell, 2002; Wan et al., 2010; Zhang et al., 2013) (Fig. 3). The earliest orthophragminids in the Salt Range are known after the Paleocene–Eocene boundary in the *Alveolina vredenburghi* Zone (SBZ 5) (Ferràndez-Cañadell, 2002). From the Tethyan Himalayas of Tibet they have been first recorded in the mid–late Ypresian (SBZ 9/10) (Zhang et al., 2013); their first occurrence from the Asian plate (Zhongba area) in Tibet has been recorded much earlier, in the late Thanetian (SBZ 4) (BouDagher-Fadel et al., 2015). In the eastern Tethys, to the southeast of Tingri and Gamba, Paleocene orthophragminids, associated with *Glomalveolina primaeva* Reichel, *Orbitosiphon punjabensis* (Davies), *Lakadongia tibetica* (Douvillé), miscellaneous, and rotaliids, have been reported only from the Lakadong Limestone in the Shillong Plateau in the Meghalaya region (e.g., Mawmluh Quarry section) (Dutta and Jain, 1980; Jauhri, 1994, 1998; Jauhri et al., 2006; Matsumaru and Jauhri, 2003; Matsumaru and Sarma, 2010; Tewari et al., 2010). These orthophragminids

were previously mainly described from axial and tangential sections in rock thin sections and were assigned to either *Discocyclus* or *Orbitoclypeus* with contrasting species-level identifications. Jauhri (1998) first mentioned the occurrence of *Orbitoclypeus ramaraoi* (*O. schopeni ramaraoi* of Less, 1987) in the Lakadong Limestone from the Um Sohryngkew River section near the Therria village in the southern Shillong Plateau, without any illustration and discussion. The orthophragminids from the same section, however, were assigned to *Discocyclus* by Jauhri et al. (2006) without any reference to *Orbitoclypeus* previously reported by Jauhri (1998). Matsumaru and Sarma (2010) recorded *Orbitoclypeus ramaraoi* in oblique sections, although these authors also incorrectly assigned some sections of *Orbitoclypeus* to *Orbitosiphon tibetica*.

Further southward along the Indian subcontinent, Paleocene orthophragminids have been recorded only from the Cauvery Basin (Pondicherry area) in SE India (Samanta, 1967). Here, the orthophragminids are represented only by *Orbitoclypeus schopeni ramaraoi*, the most primitive member of the *O. schopeni* lineage. The associated LBF assemblages of this area are poorly characterized (Govindan, 2013) and the identification of *Ranikothalia* by Samanta (1980) should be revised: his figured specimens do not show a marginal chord and appear to be rotaliids (*Daviesina*), not nummulitids. The assemblages do not permit the assignment of a precise SBZ age to these shallow-marine deposits consisting of strongly burrowed, several-meter-thick argillaceous carbonates. Records of late Paleocene orthophragminids from the Andaman Islands are similarly based on loosely dated assemblages yielding *Ranikothalia* (Koley and Wanjarwadkar, 2013).

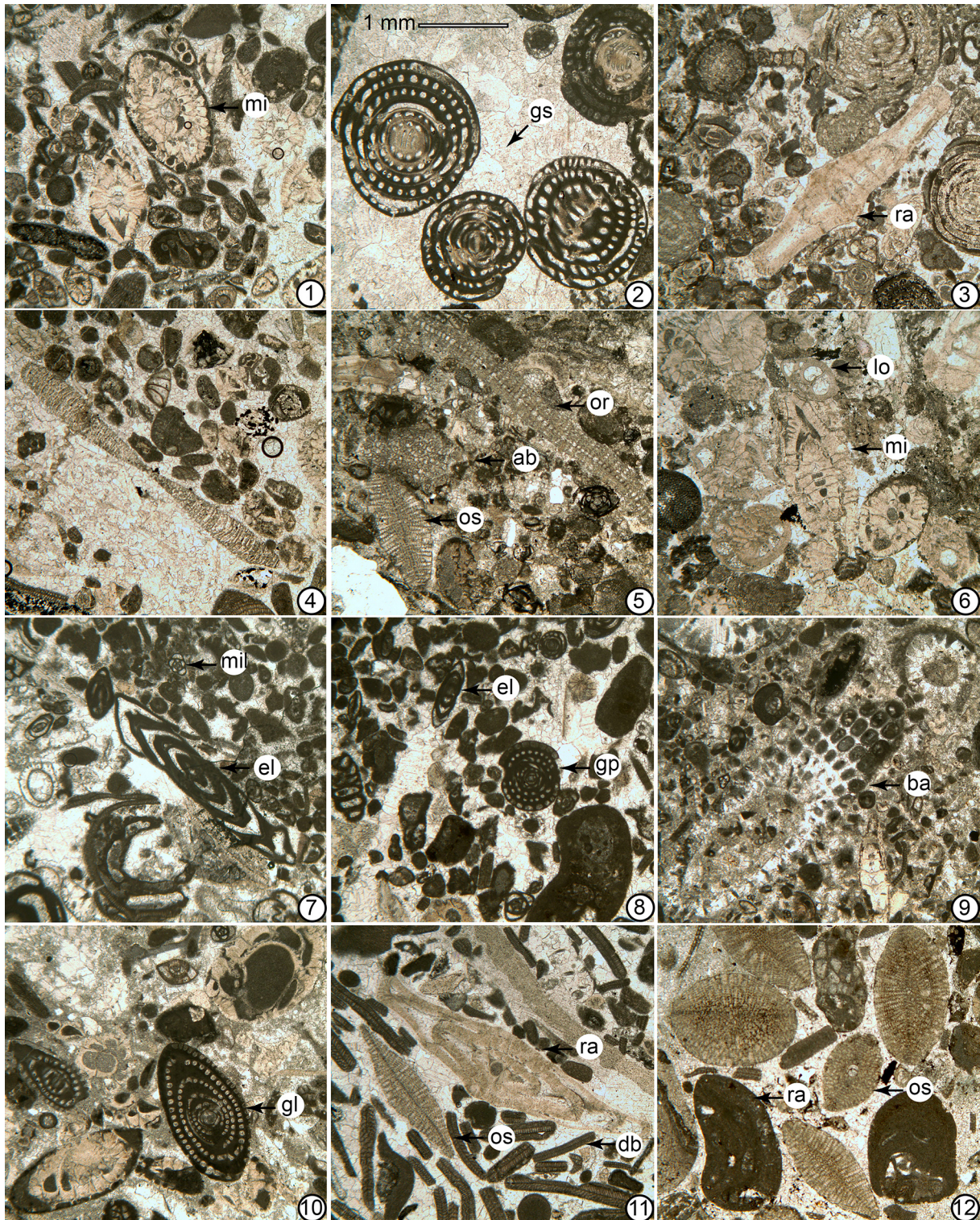
## 5 The facies, LBF, and associated fauna and flora in MQS

The Lakadong Limestone contains a diverse association of benthic foraminifera of such groups as the miscellaneids, alveolinids, orthophragminids, rotaliids, miliolids, and textulariids, accompanied by dasycladalean and coralline algae, rare corals, bryozoans, echinoids, bivalves, and gastropods (Figs. 4–6). The foraminifera are represented by the following genera: *Orbitoclypeus* Silvestri, *Lakadongia* Matsumaru and Jauhri (= *Setia* Ferrández-Cañadell, see below for detailed explanation); *Orbitosiphon* Rao; *Ornatanomalina* Haque; *Lockhartia* Davies; *Miscellanea* Pfender; *Carterella* Sirel; *Ranikothalia* Caudri; *Elazigella* Sirel; *Rotalia* Lamarck; *Aberisphaera* Wan; *Glomalveolina* Hottinger; *Rotorbinella* Bandy; *Idalina* Munier-Chalmas and Schlumberger; *Valvulina* d'Orbigny; *Orduella* Sirel; *Globotextularia* Eimer and Fickert; *Mardinella* Meriç and Çoruh (= *Azzarolina* Vicedo and Serra-Kiel); *Periloculina* Munier-Chalmas and Schlumberger; *Cincoriola* Haque; *Kathina* Smout; and *Pachyrotalia* Hottinger (Fig. 5). The unit con-

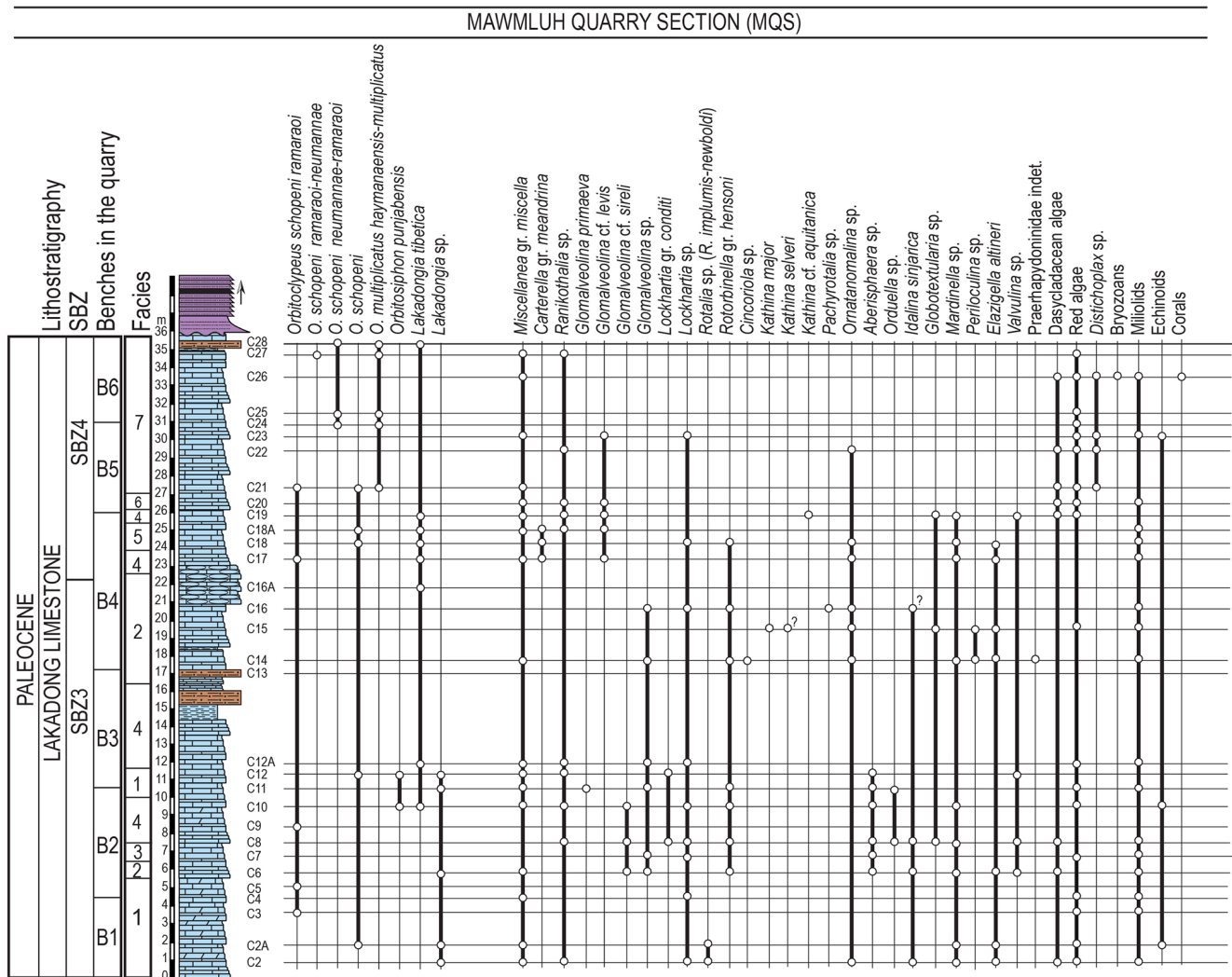
sists of wackestones–packstones dominated by LBF and coralline–dasycladacean algae, which are characteristic of inner- to middle and middle to outer shelf environments (Nebelsick et al., 2005) (Figs. 4 and 5). Most of the section, between samples 1 and 20, yielding alveolinids, miscellaneids, and rotaliids, was deposited in an inner to middle shelf setting, whereas the upper part (samples 21–28), with orthophragminids and less abundant rotaliids and miscellaneids, was deposited in a middle to outer shelf depositional setting. This suggests a general deepening upsection. Among the alveolinids, the occurrence of *Glomalveolina* cf. *sireli* and also *G. primaeva* in the lower and middle part of the section is significant for the assignment of SBZ 3. The first appearance of *Glomalveolina* cf. *levis* in sample C17 is used to place the boundary between SBZ 3 and SBZ 4, which corresponds tentatively to 22 m in the section.

Orthophragminids are scarce in the interval from the first sample of the section up to sample C20, where *Distichoplax biserialis* becomes abundant. The occurrence of *Lakadongia*, abundant in the middle part of the section below sample C21, declines sharply upward in the section, with a single record in the last sample (C28). The orthophragminids are subdivided into two lineages of the genus *Orbitoclypeus* Silvestri, the lineages of *O. schopeni* (Checchia-Rispoli) and *O. multiplicatus* (Gümbel). In the lower part of the section (SBZ 3 and lower part of SBZ 4), the specimens belonging to *Orbitoclypeus schopeni* are identified as *O. schopeni ramaraoi* based on morphometry (with an average  $D_{\text{mean}}$  value of 188.3  $\mu\text{m}$  for sample C21), whereas those in the upper part (SBZ 4) represent a transitional development stage between *O. schopeni ramaraoi* and *O. schopeni neumannae* (with average  $D_{\text{mean}}$  values ranging between 192.9 and 198.3  $\mu\text{m}$ ). The embryo diameter of *O. multiplicatus*, recorded only in SBZ 4, ranges between 300.0 and 318.3  $\mu\text{m}$  on average, corresponding to the transitional development stages of *O. multiplicatus haymanaensis* and *O. multiplicatus multiplicatus*.

Algae are essentially represented by red and green algae, among which *Distichoplax biserialis* (Dietrich) Pia is the most common in MQS (Fig. 6). Fragments of other corallineaceans also occur through the section, while crustose thalli of *Lithoporella* sp. are only recorded from sample C15 up to sample C28. *Polystrata alba* (Pfender) Denizot is occasionally found. Among green algae, dasycladales are predominant. Thyrso-porellids are rather common throughout the section and include *Thyrso-porella turgidipora* Radoičić, *Belzungia pfenderae* Radoičić, and Özgen-Erdem, *Belzungia* cf. *terquemi* Morellet and Morellet, *Dissocladella gracilis* Radoičić and *Furcoporella diplopora* Pia, the latter species being found only in the middle and upper part of the section. Among neomerids, *Indopolia* cf. *satyavanti* Pia and *Cy-mopolia* aff. *sirmiense* Radoičić are recorded. Acetabulariaceans are characterized by *Clypeina rotella* Wang, *Acicularia tavnae* Radoičić, and *Orioporella malaviae* Pia. Apart from *Ovulites morelleti* Elliott commonly occurring in the



**Figure 4.** Thin-section photomicrographs of foraminiferal and algal assemblages in the Lakadong Limestone. 1: miscellaneid foraminifer-red algal wackestone-packstone with miscellaneids (mi); 2–3, 7–8: *Glomalveolina*-dasycladalean algae–miliolid wackestone-packstone with *Glomalveolina* cf. *sireli* (gs), *Glomalveolina primaeva* (gp), *Ranikothalia* sp. (ra), *Elazigella altineri* (el), and miliolids (mil); 4, 6, 9–10: miscellaneid foraminifera-*Glomalveolina* wackestone-packstone with *Lockhartia* sp. (lo), miscellaneids (mi), *Bakalovaella* sp. (ba), *Glomalveolina levis* (gl); 5: *Aberisphaera*-red algal wackestone-packstone with *Aberisphaera* sp. (ab), *Orbitoclypeus schopeni* (os) and *Orbitosiphon pubjabensis* (or); 11–12: orthophragminid-red algal-*Distichoplax* packstone-grainstone with *Ranikothalia* sp. (ra), *Orbitoclypeus schopeni* (os), *Distichoplax biserialis* (db) and red algae (ra). 1: sample C2; 2: sample C6; 3: sample C8; 4: sample C10; 5: sample C12; 6: sample C12A; 7: sample C15; 8: sample C16; 9: sample C17; 10: sample C19; 11: sample C22; 12: sample C23.



**Figure 5.** Lithostratigraphic column of the Lakadong Limestone in MQS, facies, and distribution of LBF and other fossil groups with inferred SBZ zones by Serra-Kiel et al. (1998). Facies explanation: 1: miscellaneids-red algal wackestone–packstone, 2: *Glomalveolina*-dasycladalean algae-miliolid wackestone–packstone, 3: *Aberisphaera*-red algal wackestone–packstone, 4: miscellaneids-*Glomalveolina* wackestone–packstone, 5: *Lakadongia*-*Glomalveolina* wackestone–packstone, 6: dasycladalean algal wackestone, 7: orthophragminid-red algal- *Distichoplax* packstone–grainstone.

lower-middle part of the section, other green algae bryopsidales are found in the upper part and consist of disc-like segments of *Halimeda* cf. *tuna* Lamouroux and a large specimen tentatively identified as *Arabicodium* sp. Dasycladaleans inhabit shallow warm waters (Valet, 1979) in particular thyrsoeporellids are interpreted to prefer mid-ramp environments (Barattolo, 2002). Many taxa recognized in the MQS are characteristic for European and North African Thanetian–Ypresian successions. *Indopolia satyavanti*, *Orioporella malaviae*, and *Clypeina rotella* are recognized here for the first time from the NE Indian area. The latter species, recorded only at its type locality in Tibet, is poorly known.

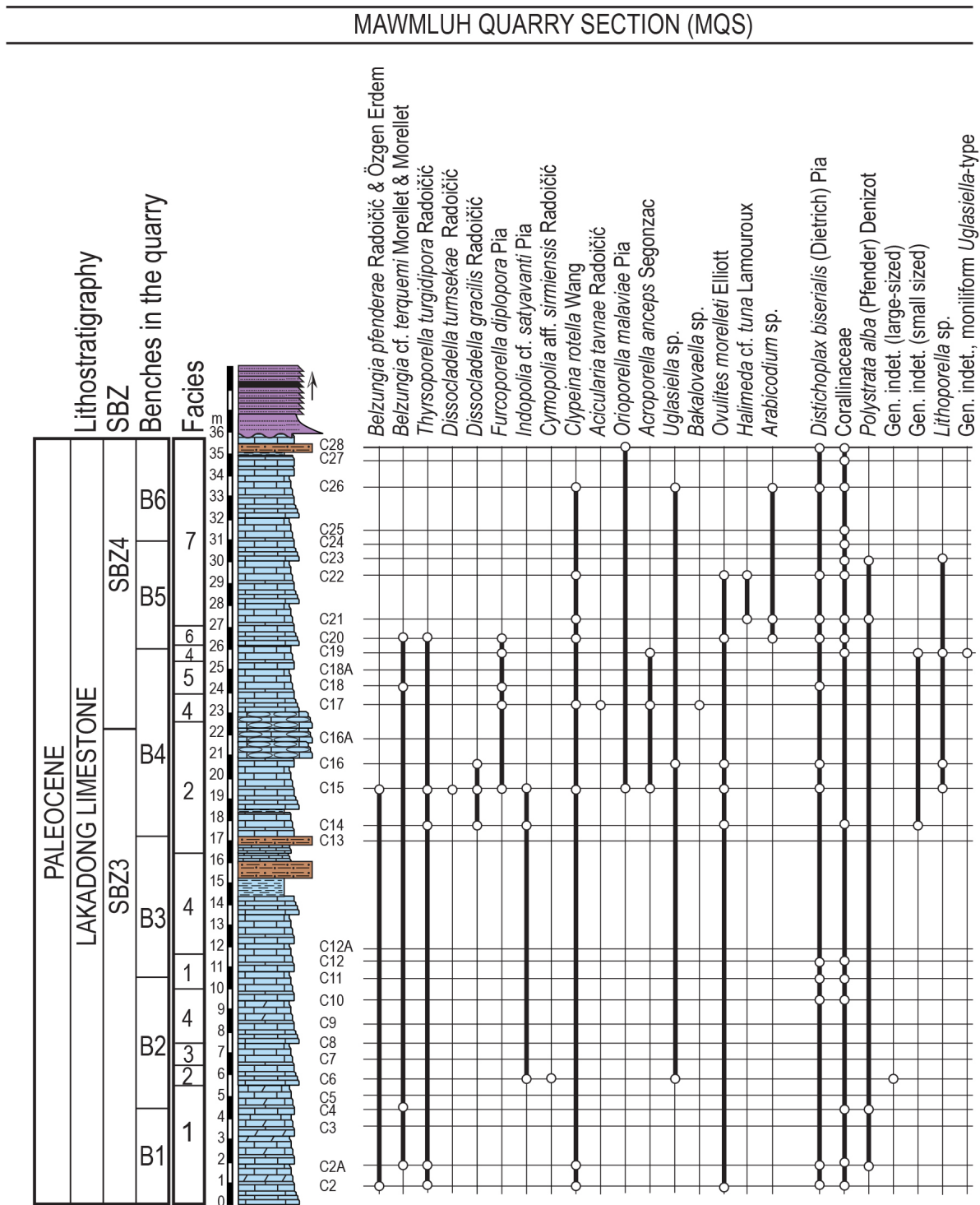
## 6 Systematic paleontology

We follow the taxonomic concept adopted for western Tethyan Paleocene orthophragminids by Less (1987) and Less et al. (2007). The details of morphometric discrimination of subspecies in orthophragminids are explained in Less and Kovács (2008). Eight test measurements (in micrometers) and counts and some qualitative data (e.g., types of embryon configurations and adauxiliary chamberlets) were used to characterize the taxa (Fig. 7 and Table 1). These measurements and counts are  $P$  and  $D$ , outer diameter of the protoconch and deuteroconch perpendicular to their common axis;  $A$ , number of adauxiliary chamberlets;  $H$  and  $W$ , height and width of the adauxiliary chamberlets;  $n_{0.5}$ , number of annuli

**Table 1.** Statistical data for the orthophragminids from the Lakadong Limestone. For the illustration and explanation of the parameters, see Fig. 7c. *N* denotes the number of specimens studied in each sample. Asterisks indicate the measurements from random thin sections.

Sample	<i>N</i>	Outer cross diameter of the embryo			Auxiliary chamberlets			Equatorial chamberlets			Species/subspecies	
		Deuteroconch		Protoconch	Number		Height	Width	Annuli	Height		Width
		<i>D</i>	<i>P</i>	<i>A</i>	<i>H</i>	<i>w</i>	<i>n</i> 0.5	<i>h</i>	<i>w</i>			
		Mean ± SE	Range	Range	Range	Range	Range	Range	Range	Range		
C3	1	190									<i>O. schopeni</i> cf. <i>ramaraoi</i>	
C5	1	180										
C9	1	170										
C21*	3	188.3 ± 5.93	110–130									
C24	48	150–230	196.8 ± 2.71	90–145	119.38	13–23	30–50	25–35	15–17	75–80	25–35	<i>O. schopeni</i> <i>ramaraoi-neumannae</i>
C25	26	175–235	198.3 ± 3.27	95–150	115.77	13–22	30–50	25–35	16–19	45–90	25–40	
C27	12	160–230	192.9 ± 6.11	95–150	119.58	16–20	40–50	25–35	14–18	55	20–35	
C28	46	145–235	197.4 ± 2.57	95–155	119.11	17–23	20–50	25–45	15–21	55–65	20–40	
C21*	10	280–360	301.0 ± 6.70	150–185	167							<i>O. multiplicatus</i> <i>haymanaensis-multiplicatus</i>
C24	6	260–400	318.3 ± 17.06	150–210	189	24–26	40–60	25–50	7–11	35–80	25–45	
C25	1		250		150				14			
C27	2	280–320	300.0 ± 14.14	130–170	150	26–32	50–65	25–50	9–11	55–75	20–40	
C28	8	255–390	311.2 ± 17.09	140–255	175	25–29	50–60	25–55	9–10	60–75	25–35	





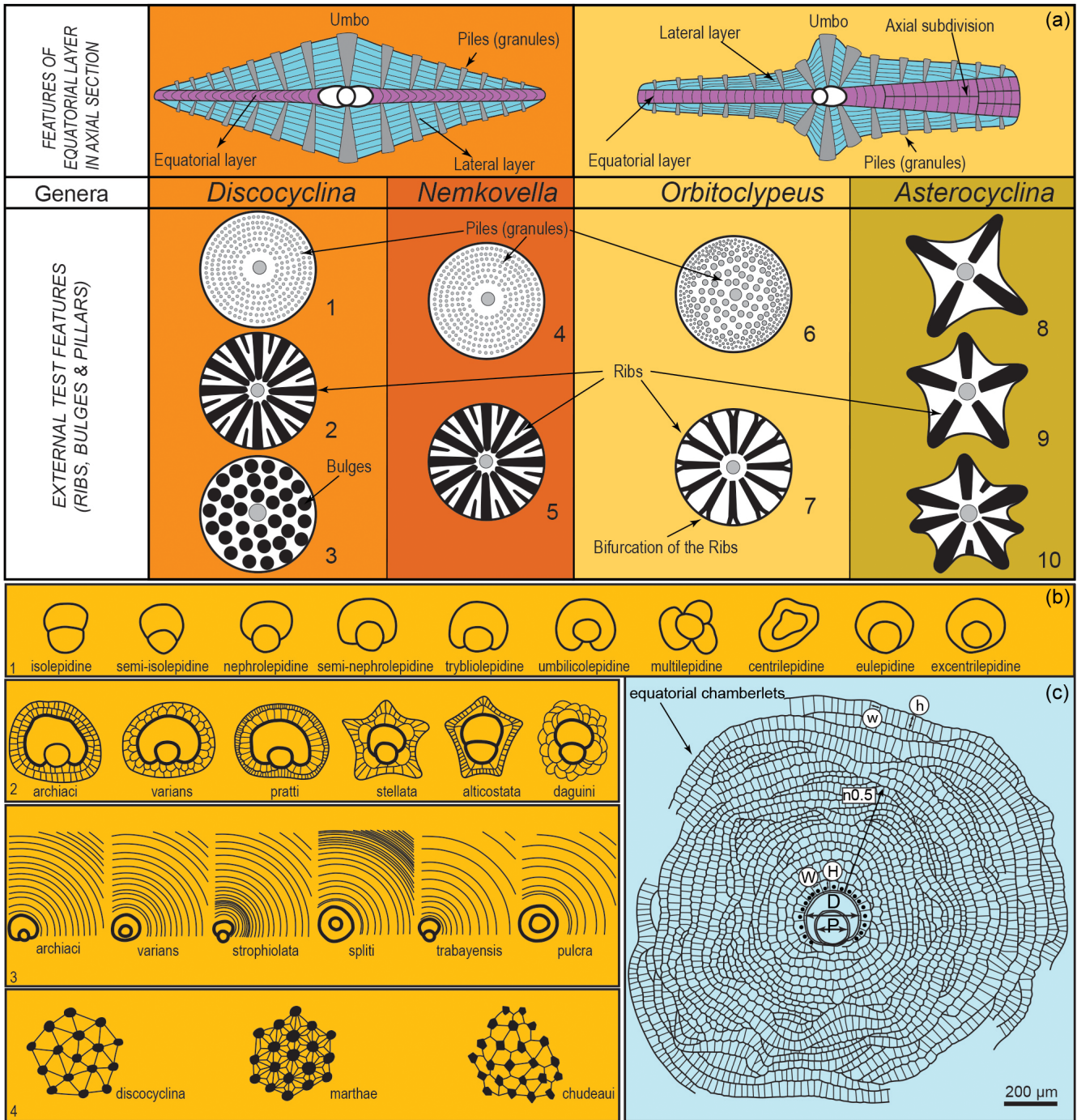
**Figure 6.** Distribution of algae in MQS. See Fig. 5 for facies explanation.

within a 0.5 mm distance measured from the deuteroconch along the axis of the embryo; and *h* and *w*, height and width of the equatorial chamberlets around the peripheral part of the equatorial layer.

Order **Foraminiferida** Eichwald

Family **Orbitoclypeidae** Brönnimann

Genus *Orbitoclypeus* Silvestri



**Figure 7.** (a) General test features in Tethyan orthophragminid genera (after Less, 1987; Ferrández-Cañadell, 1997; Özcan et al., 2016b). (b) Qualitative parameters: 1: types of embryon configurations; 2: types of adauxiliary chamberlets; 3: different growth patterns of the equatorial annuli; 4: types of granules and lateral chamberlets on the test surface; and (c) parameters used in the morphometric description of orthophragminids as illustrated in *Orbitoclypeus schopeni ramaraoi-neumannae* from MQS.

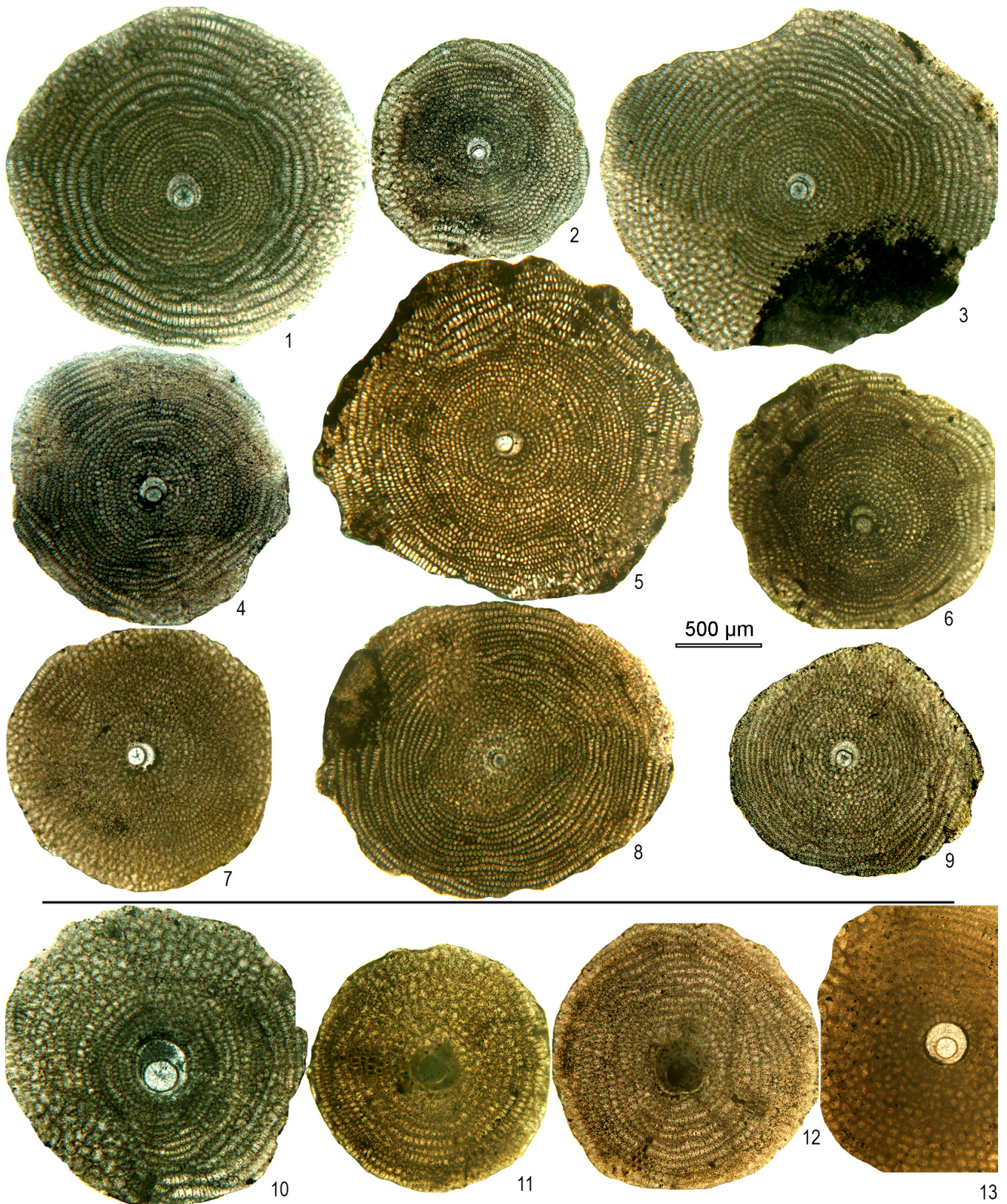
*Orbitoclypeus schopeni* (Checchia-Rispoli, 1908)

**Diagnosis:** *Orbitoclypeus schopeni* is an unribbed species with a “marthae” type rosette, a small to relatively large, eu-, tryblio-, and excentrolepidine embryon; narrow or medium

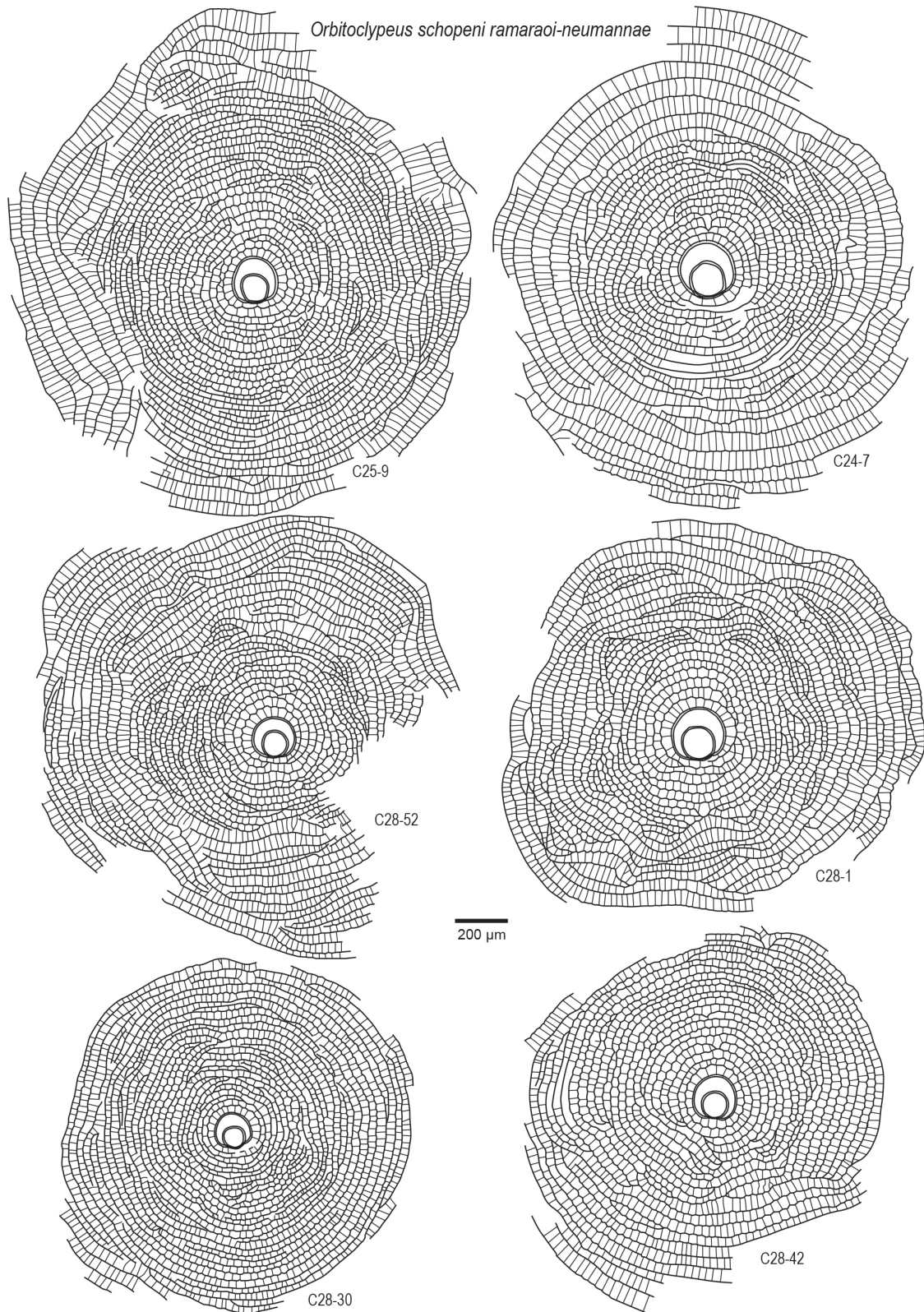
wide, low or medium high “variens” type adauxiliary chamberlets; and also narrow or medium wide equatorial chamberlets arranged into circular or slightly undulated annuli usually with variens type growth pattern. The distal margins of the



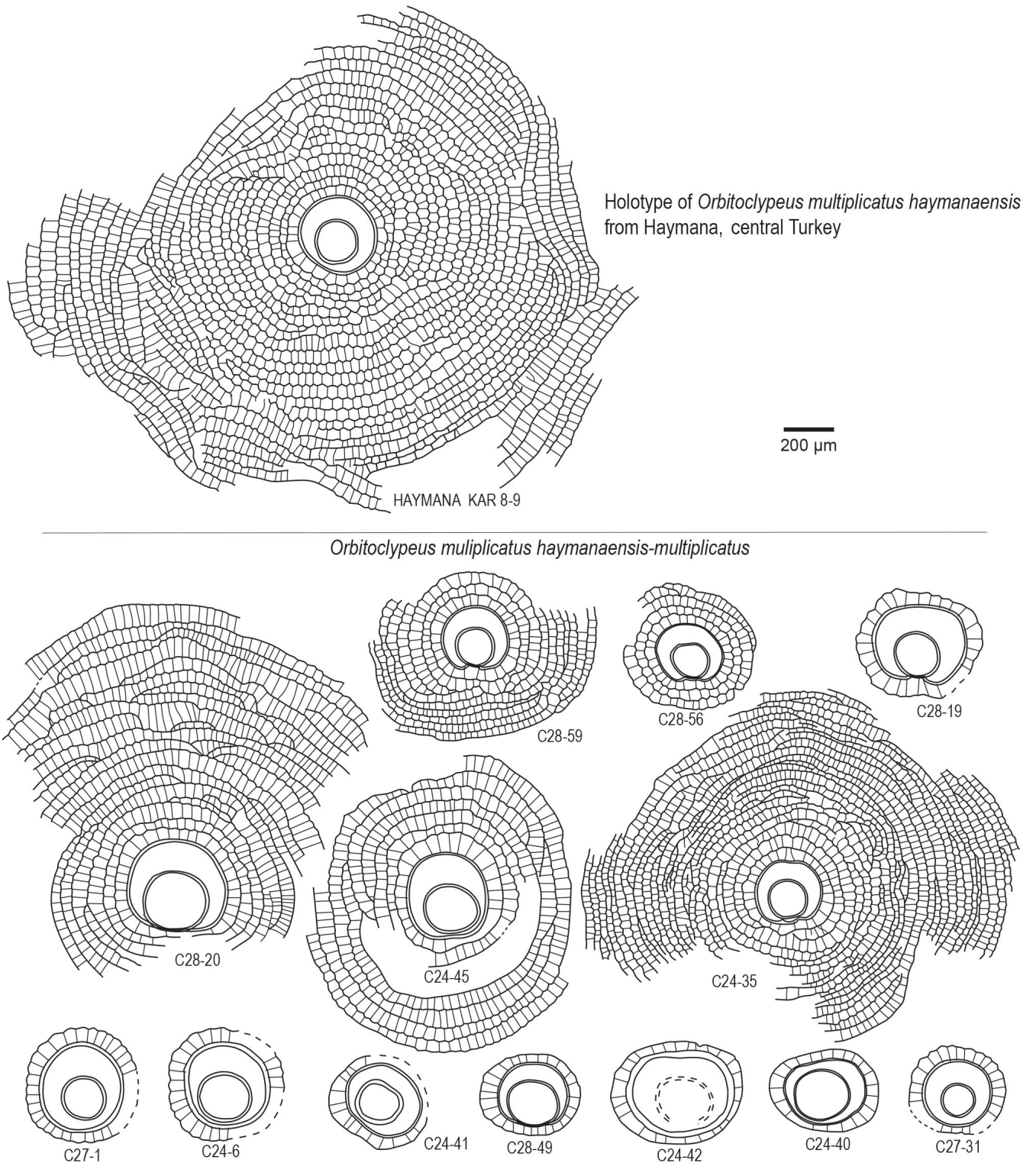
**Figure 8.** 1–2, 9–13, 22–24: *Orbitoclypeus schopeni ramaraoi-neumannae*; 1–2: external views, 9–13: axial sections, 22–24: equatorial sections of B forms. 1: C28–42, 2: C28–43, 9: C24–43, 10: C25–30, 11: C27–30, 12: C22–19, 13: C21, 22: C24–3, 23: C24–39, 24: C24–38. 3–8: *Orbitoclypeus schopeni* cf. *ramaraoi*; 3–4: equatorial sections, 3: C5–1, 4: C9–1. 5: slightly oblique equatorial section, C3–1. 6: axial section, C18, 7–8: off-center axial sections, 7: C2A, a microspherical form, 8: C12. 14–21: *Orbitoclypeus multiplicatus haymanaensis-multiplicatus*; axial to slightly off-center axial sections, 14: C21, 15: C21, 16: C21, 17: C21, 18: C21, 19: C21, 20: C28, 21: C28.



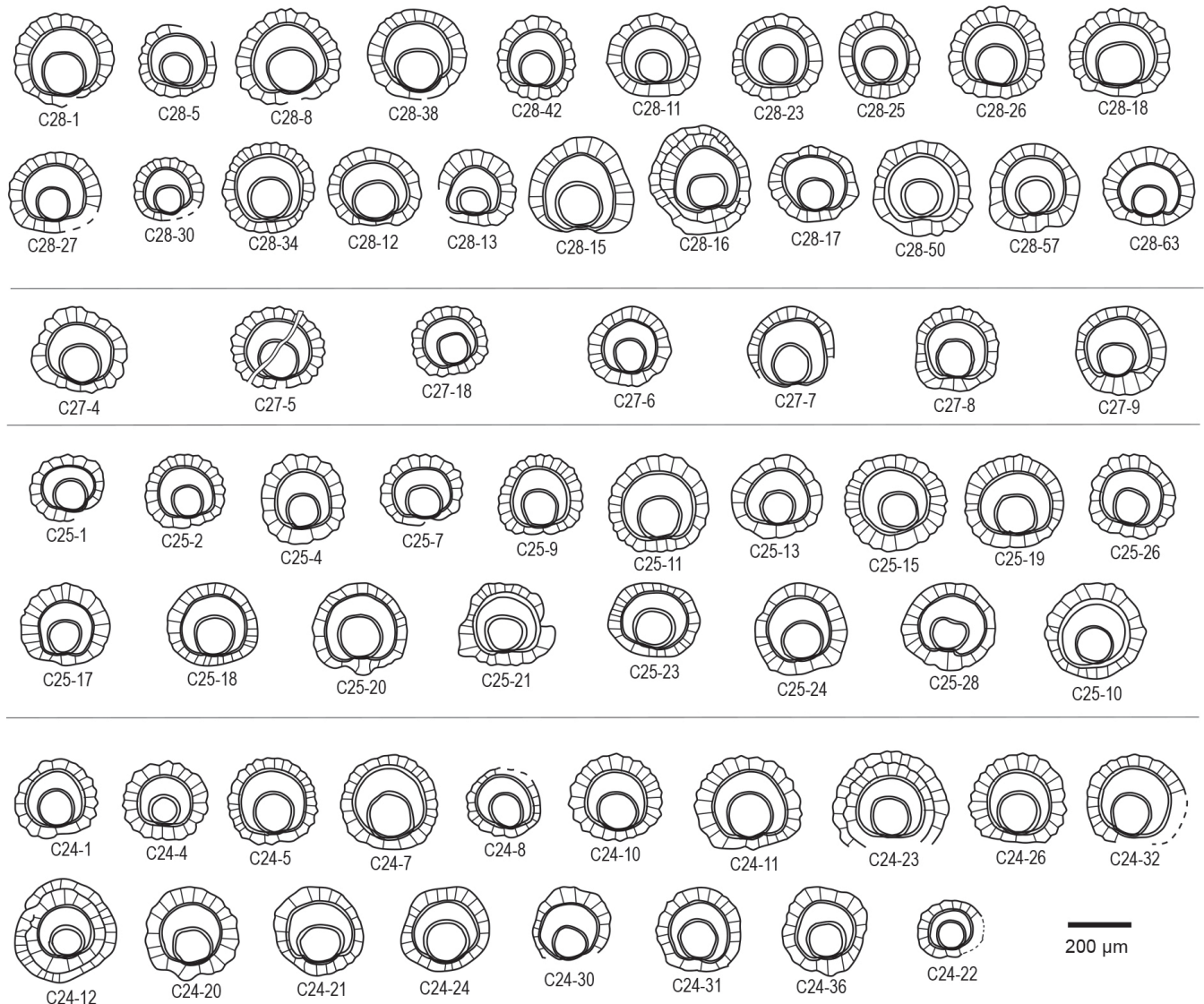
**Figure 9.** 1–9: *Orbitoclypeus schopeni ramaraoi-neumannae*; equatorial sections, 1: C24–7, 2: C24–4, 3: C24–20, 4: C24–12, 5: C25–9, 6: C24–20, 7: C24–36, 8: C25–1, 9: C25–26. 10–13: *Orbitoclypeus multiplicatus haymanaensis-multiplicatus*; equatorial sections, 10: C24–6, 11: C24–41, 12: C24–45, 13: C27–31.



**Figure 10.** Embryon and equatorial chambers in *Orbitoclypeus schopeni ramaraoi-neumannae*. Note that the embryon is of eulepidine type, some equatorial chambers are incomplete and slightly wavy in pattern, and the distal sides of the chamberlets are arcuate to wedge shaped.



**Figure 11.** Embryon and equatorial chambers in *Orbitoclypeus multiplicatus haymanaensis-multiplicatus*. Note that the embryo is of excentrilepidine, umbilicolepidine, and trybliolepidine type, the equatorial chambers are incomplete, the distal sides of the chamberlets are arcuate to wedge shaped, and the peripheral chambers are radially elongated. The holotype of *Orbitoclypeus multiplicatus haymanaensis* from the Thanetian of Haymana Basin (central Turkey), sample KAR.8, is illustrated for comparison (Özcan et al., 2001).

*Orbitoclypeus schopeni ramaraoi-neumannae*

**Figure 12.** Variation in the embryo and configuration of the embryonic chambers in *Orbitoclypeus schopeni ramaraoi-neumannae* in samples C24, 25, 27, and 28.

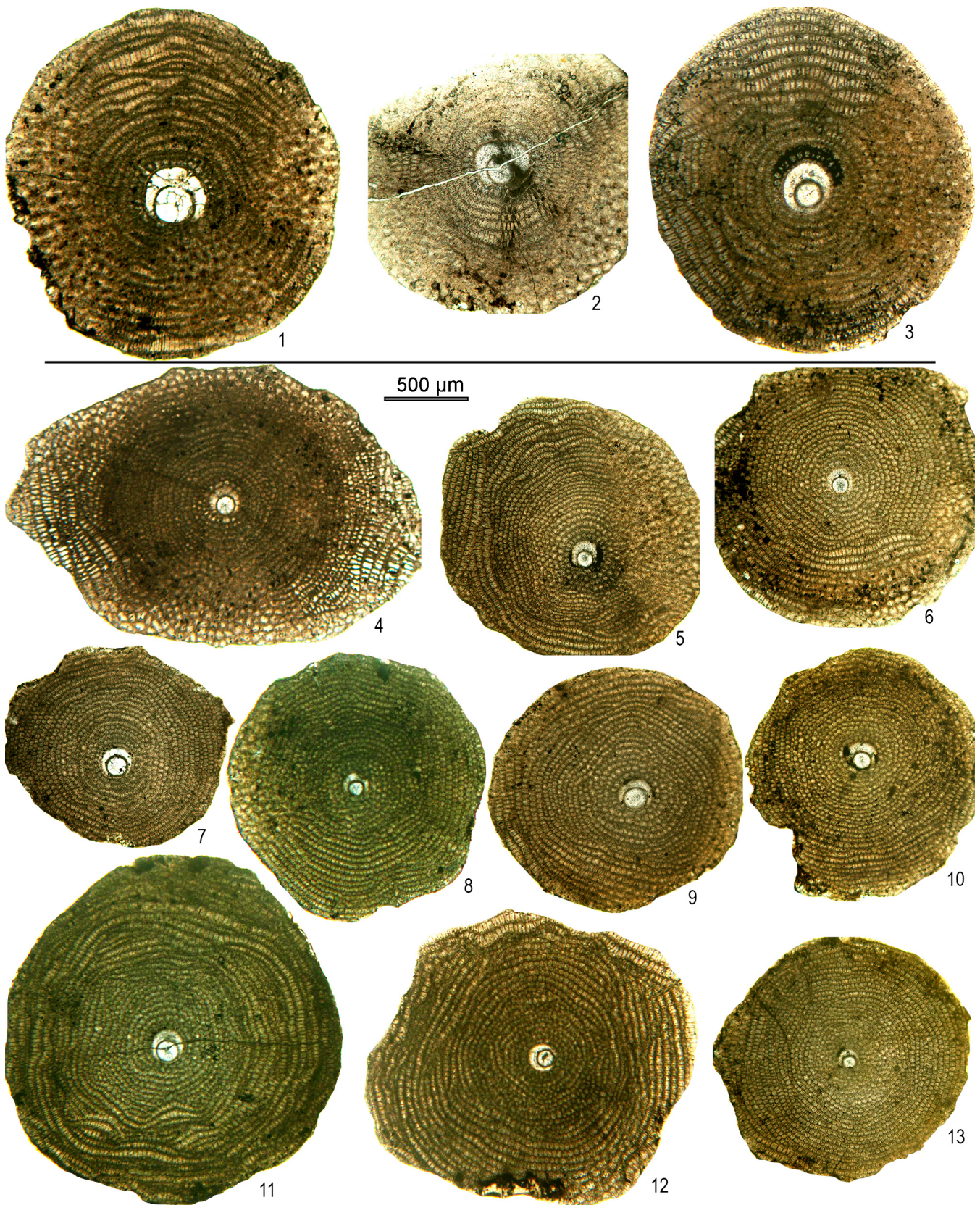
annular chamberlets are typically arched or wedge shaped. It commonly occurs in the orthophragminid assemblages from SW France to India, especially in the Thanetian and Ypresian. The earliest appearance is known from the lower Thanetian beds from India and SW France, with its reported highest occurrence from the late Lutetian (OZ 11) of Padragkút (Hungary) and San Pancrazio (OZ 12) (Italy). This species includes five subspecies in western Tethys: *O. s. ramaraoi* Samanta ( $D_{\text{mean}} < 195 \mu\text{m}$ ), *O. s. neumannae* Toumarkine ( $D_{\text{mean}} = 195\text{--}240 \mu\text{m}$ ), *O. s. suvlukayensis* Less ( $D_{\text{mean}} = 240\text{--}300 \mu\text{m}$ ), *O. s. crimensis* Less ( $D_{\text{mean}} = 300\text{--}500 \mu\text{m}$ ), and *O. s. schopeni* Checchia-Rispoli ( $D_{\text{mean}} > 500 \mu\text{m}$ ).

*Orbitoclypeus schopeni* (Checchia-Rispoli, 1908) *ramaraoi* (Samanta, 1967)-*neumannae* (Toumarkine, 1967): figs. 8.1–2, 9–13, 9.1–9, 10, 12, 13.4–13.

1967 *Discocyclina ramaraoi* n. sp. – Samanta: pp. 239–240, pl. 1, figs. 1–20, text-figs. 2–5.

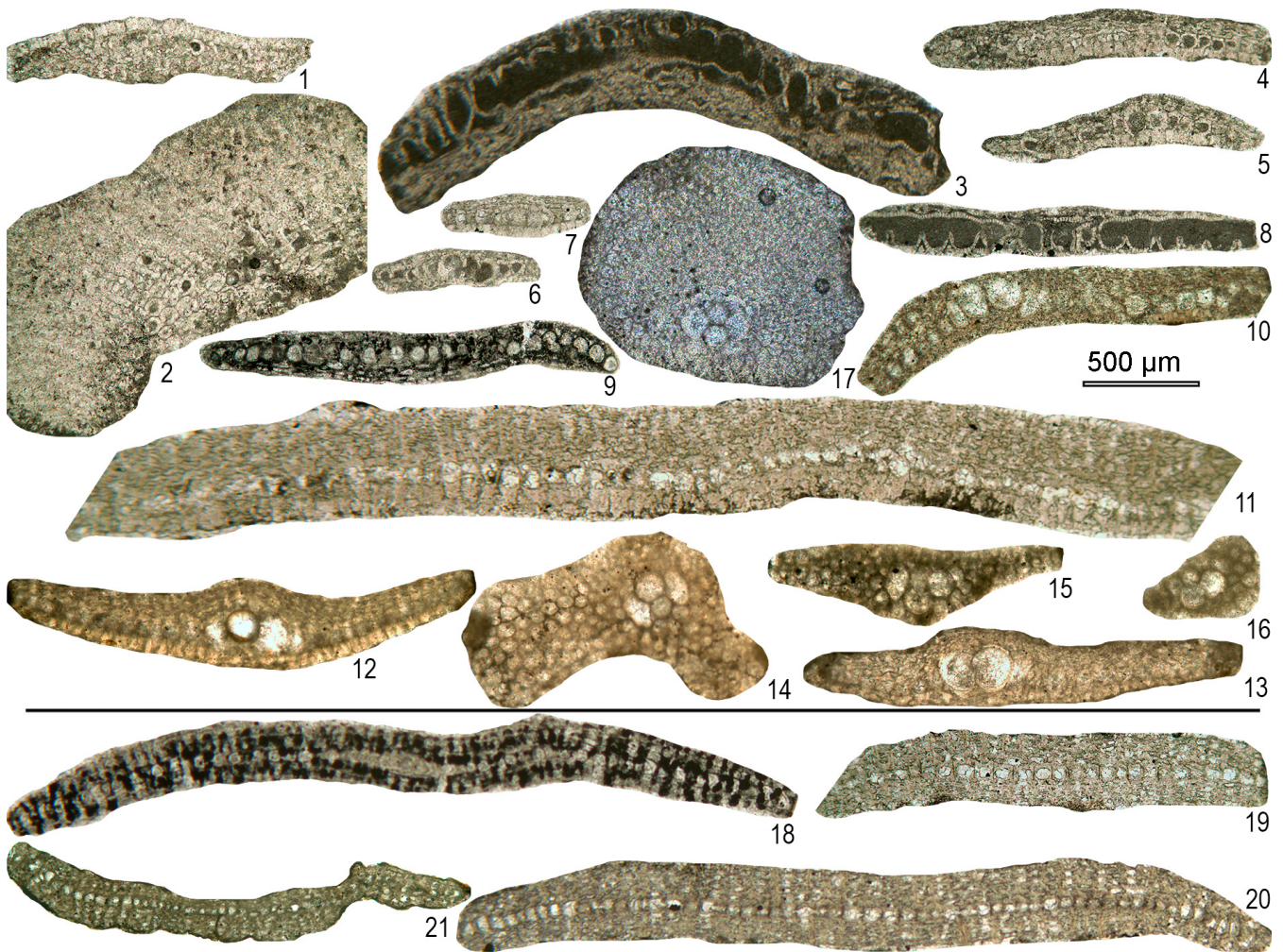
1967 *Discocyclina neumannae* n. sp. – Toumarkine: pp. 210–212, pl. 1, figs. 1–8.

1987 *Orbitoclypeus ramaraoi ramaraoi* (Samanta) – Less: pp. 197–198, text-fig. 30b.



**Figure 13.** 1–3: *Orbitoclypeus multiplicatus haymanaensis-multiplicatus*; equatorial sections, 1: C28–20, 2: C28–19, 3: C27–1. 4–13: *Orbitoclypeus schopeni ramaraoi-neumannae*; equatorial sections, 4: C28–23, 5: C28–27, 6: C28–42, 7: C28–34, 8: C28–5, 9: C28–18, 10: C28–17, 11: C28–1, 12: C28–25, 13: C28–30.





**Figure 14.** Orbitoidiform foraminifers from the Lakadong Limestone. 1–5: *Lakadongia* sp.; 1, 3–5; off-center axial sections, 1: C2–23, 3: C2A-1, 4: C2A-13, 5: C2A-18, 2: section showing equatorial chambers, C2–39. 6–17: *Lakadongia tibetica*; 6–11; off-center axial sections, 6: C10–1, 7: C11–6, 8: C11–10, 9: C12–25, 10: C18–8, 11: C18A-4. 12–13: axial sections, 12: C18–3, 13: C16–62. 14–17: incomplete equatorial sections. 14: C12–9, 15: C12–7, 16: C16A–1, 17: C16. 18–21: *Orbitosiphon punjabensis*; off-center axial sections, 18: C10–4, 19: C12–1, 20: C12–20, 21: C8–4.

1987 *Orbitoclypeus ramaraoi* (Samanta) *neumannae* (Toumarkine) – Less: pp. 198–199, pl. 26, figs. 1, 2, text-fig. 30c.

2001 *Orbitoclypeus neumannae* (Toumarkine) – Özcan et al.: pp. 347, 348, 350, pl. 1, figs. 14–16, pl. 2, figs. 1–8, text-fig. 3C.

2007 *Orbitoclypeus schopeni* (Cecchia-Rispoli) *ramaraoi* (Samanta) – Less et al.: pp. 441–442, pl. 3, figs. 20–22, Fig. 14.

2007 *Orbitoclypeus schopeni* (Cecchia-Rispoli) *neumannae* (Toumarkine) – Less et al.: pp. 441–442, pl. 3, figs. 19, 23–29, Fig. 14.

2010 *Orbitoclypeus ramaraoi* (Samanta) – Matsumaru and Sarma: pl. 6, fig. 8.

2010 *Orbitosiphon tibetica* (Douvillé) – Matsumaru and Sarma: pl. 1, fig. 3.

2014 *Orbitoclypeus schopeni* (Cecchia-Rispoli) *ramaraoi* (Samanta) – Özcan et al.: pp. 224–225, fig. 12.10–14, fig. 13–14, fig. 15.13–16.

Both the megalospheric (A forms) and microspherical (B forms) specimens have been studied, though the microspherical generation is rare and only five specimens were found among 143. The test is of medium size, circular in outline, mostly symmetrical with regard to the equatorial layer, and lenticular discoidal. The test diameter and thickness in A forms range between 1050 and 2800 and between 350 and 780 µm, respectively (Fig. 8.7–13). In the lower part of the section (e.g., samples C3, 5, 9), the specimens (*O. schopeni* cf. *ramaraoi*) have smaller tests, varying in

diameter from 600 to 1200  $\mu\text{m}$  (Fig. 8.3–6). The surface is smooth with uniformly distributed piles, coarser at the central part of the test (70–90  $\mu\text{m}$  in diameter) and finer towards the periphery (20–50  $\mu\text{m}$  in diameter). A large pile, 100–110  $\mu\text{m}$  in diameter, is usually observed at the center of the test. The equatorial layer is about 35–60  $\mu\text{m}$  high in axial sections. The average diameters of protoconch and deuteroconch range between 115.7–119.5  $\mu\text{m}$  and 192.9–198.3  $\mu\text{m}$ , respectively (Table 1). Both chambers invariably exhibit a eulepidine-type embryonic configuration. The number of adauxiliary chamberlets counted in 132 specimens varies between 13 and 23. The equatorial chamberlets are low and narrow in the early chambers and become radially elongated in the outer chambers. These chambers are slightly wavy in the equatorial sections and they usually form incomplete cycles (Fig. 10). The microspherical generation possesses a typical orbitoclypeid juvenarium, as shown in Fig. 8.22–24.

**Remarks:** Specimens from the lower part of the Lakadong Limestone (samples C3, 5, 9), as well as upper samples below sample C21 (Fig. 8.3–8), were assigned to *Orbitoclypeus schopeni* cf. *ramaraoui* due to sparse morphometric data from these levels. Specimens from the upper part (SBZ 4) represent transitional development stages between *O. schopeni ramaraoi* and *O. schopeni neumannae* with average  $D_{\text{mean}}$  values ranging between 192.9 and 198.3  $\mu\text{m}$  (Table 1). *Orbitoclypeus schopeni* is differentiated from *O. multiplicatus* in having (a) a smaller embryo, (b) a different type of embryonic configuration (eulepidine in *O. schopeni* and excentrilepidine to umbilicolepidine type in *O. multiplicatus*), (c) a smaller number of adauxiliary chamberlets, and (d) smaller equatorial chambers/chamberlets, as recorded in parameter  $N_{0.5}$ . The average deuteroconch size of this species from SBZ 4 in MQS is slightly above the morphometric limit between *O. s. ramaraoi*, which stratigraphically extends to the early Eocene in the western Tethys, and *O. s. neumannae*. These records suggest that the average deuteroconch size of *O. schopeni* might be slightly larger than that in the western Tethys (Table 2).

In previous works, *Orbitoclypeus* from the Lakadong Limestone has been apparently confused with the genera *Discocyclina* and *Lakadongia*. Matsumaru and Sarma (2010) illustrated several embryos in equatorial and uncentered equatorial sections as *Orbitosiphon tibetica* (Douvill ) from the Lakadong Limestone in Meghalaya. In fact, these specimens with different embryonic configurations and different features of equatorial chamberlets represent three different genera. The biloculine specimens illustrated in Plate 1, figs. 1 and 2 in Matsumaru and Sarma (2010) were correctly assigned to *Orbitosiphon tibetica* by the authors. The uncentered specimen with eulepidine embryo (fig. 3) represents an *Orbitoclypeus schopeni ramaraoi* and the specimen with isolepidine embryo and hexagonal peripheral chamberlets illustrated in fig. 4 represents a *Nemkovella stockari* Less &  zcan (see  zcan et al., 2016a). We think that the strati-

graphic position of *Nemkovella stockari*, an early Eocene species as recorded in several localities (e.g., Turkey, Tunisia, Egypt, and Oman) in the western Tethys, has also been confused by the authors. The alleged occurrence of *Discocyclina* in the Lakadong Limestone (e.g., Jauhri et al., 2006) is not confirmed by the present study. Previous records of orthophragminids from Pondicherry (SE India), the Salt Range (Pakistan), Gamba and Tingri (Tibet) (Samanta, 1967; Hu et al., 1976; Wan, 1991; Ferr andez-Cañadell, 2002; Wan et al., 2010; Zhang et al., 2013), and the late Paleocene and early Eocene assemblages from the Indian subcontinent ( zcan et al., 2015, and this study) suggest that the genera *Discocyclina* and *Orbitoclypeus* do not co-occur in the Paleocene of the eastern Tethys. The co-occurrence of both genera is known from the *Alveolina vredenburgi* beds (SBZ 5) in the Salt Range and lower Eocene Patala Formation in Thal in Pakistan ( zcan et al., 2015; Ercan  zcan, unpublished data, 2015).

*Orbitoclypeus multiplicatus* (G mbel, 1870)

**Diagnosis:** Average-sized, inflate, unribbed forms with marthae type rosette. The medium-sized to moderately large embryo is in most cases excentrilepidine, rarely eulepidine. The numerous varians type adauxiliary chamberlets as well as the equatorial chamberlets are rather wide and of average height. The annuli are usually moderately undulated; the growth pattern is of the varians type. This species includes four subspecies in the western Tethys: *O. m. haymanaensis*  zcan, Sirel,  zcan-Altner and  olakođlu ( $D_{\text{mean}} < 310 \mu\text{m}$ ); *O. m. multiplicatus* G mbel ( $D_{\text{mean}} = 310\text{--}420 \mu\text{m}$ ); *O. m. kastamonuensis* Less and  zcan ( $D_{\text{mean}} = 420\text{--}550 \mu\text{m}$ ), and *O. m. gmundenensis* Less ( $D_{\text{mean}} > 550 \mu\text{m}$ ).

*Orbitoclypeus multiplicatus* (G mbel, 1870) *haymanaensis*  zcan et al., 2001 -*multiplicatus* (G mbel, 1870): Figs. 8.14–21, 9.10–13, 11, 13.1–3.

2001 *Orbitoclypeus haymanaensis* n. sp. –  zcan et al.: pp. 344–345, 347, pl. 1, figs. 1–13, text-fig. 3A.

2007 *Orbitoclypeus multiplicatus* (G mbel, 1870) *haymanaensis*  zcan, Sirel,  zcan-Altner and  olakođlu, 2001 – Less et al.: pp. 439, pl. 3, figs. 1–3; Fig. 14.

2007 *Orbitoclypeus multiplicatus multiplicatus* (G mbel, 1870) – Less et al.: pp. 439, pl. 3, figs. 5–9, 11–13; Fig. 14.

2014 *Orbitoclypeus multiplicatus* (G mbel, 1870) *haymanaensis*  zcan, Sirel,  zcan-Altner and  olakođlu, 2001 –  zcan et al.: pp. 223, figs. 12, 15–19, 21–25, Figs. 13–14, 19.

Only megalospheric (A forms) specimens have been found. The test is of medium size, circular in outline,

**Table 2.** Statistical data for *O. schopeni ramaraoi* from western Tethys. “No.” denotes the number of specimens studied in the samples.

Sample & locality	SBZ and Reference	No.	$P_{\text{mean}}$	$D_{\text{mean}}$
KURUC-Turkey	SBZ 5 (Less et al., 2007)	18	106.2	185.8
KAR.8-Turkey	SBZ 3–4 (Özcan et al., 2001)	20	108.5	183.4
KAR.9-Turkey	SBZ 3–4 (Özcan et al., 2001)	12	115.0	188.7
D6.37-Egypt	SBZ 3–4 (Özcan et al., 2014)	4	100.0	181.2
D8.20-Egypt	SBZ 3–4 (Özcan et al., 2014)	5	91.7	173.0
D5.38-Egypt	SBZ 3–4 (Özcan et al., 2014)	5	98.0	185.0
B3.41-Egypt	SBZ 3–4 (Özcan et al., 2014)	7	95.8	185.7
NTSOR-France	SBZ 3 (Less et al., 2007)	4	137.5	192.5
RUBEC-France	SBZ 3 (Less et al., 2007)	11	108.6	184.5

mostly symmetrical with regard to the equatorial layer, and lenticular discoidal with a lobate periphery. The external test features are similar to those of *O. schopeni* and a clear distinction based on these features between these two species is not possible. The test diameter and thickness in A forms range between 1780 and 2050 and between 650 and 800  $\mu\text{m}$ , respectively (Fig. 8.14–21). The surface is smooth with uniformly distributed piles, coarser in the central part of the test (50–100  $\mu\text{m}$  in diameter) and finer towards the periphery (30–50  $\mu\text{m}$  in diameter). A large pile is usually present at the center of the test. The equatorial layer is about 50–55  $\mu\text{m}$  high in axial sections. The average diameters of the protoconch and deutoconch range between 150.0–189.0 and 300.0–318.3  $\mu\text{m}$ , respectively (Table 1). Both chambers exhibit excentrolepidine to umbilicolepidine embryonic configuration (Fig. 11). The number of adauxiliary chamberlets counted in 27 specimens varies between 24 and 32. The equatorial chamberlets are relatively high and wide in the early chambers and may become radially elongated in the outer chambers. These chambers are slightly wavy in the equatorial sections and they usually form incomplete cycles (Fig. 11).

**Remarks:** *O. multiplicatus*, identified only in the upper part of the MQS, is much less abundant than *O. schopeni*. A distinction between *O. multiplicatus* and *O. schopeni* based on external characters is unfeasible because of the same test features; these species can be differentiated only in equatorial and axial sections. Less et al. (2007) indicated that the morphology and the evolutionary track of *Orbitoclypeus multiplicatus* and *O. schopeni* and *O. varians* are very similar. Therefore, the assignment of a given population to any of these three species is based mainly on the accompanying fossils. Moreover, they all gave rise to coeval lineages with ribs such as *O. bayani*, *O. munieri*, and *O. furcatus*, respectively, that are also very similar to each other.

## 7 The orbitoidiform foraminifera in MQS

The orbitoidiform foraminifera in MQS include two genera, *Lakadongia* Matsumaru and Jauhri, 2003, very common in SBZ 3 and rare in SBZ 4, and sparse *Orbitosiphon* Rao in SBZ 4 (Figs. 5 and 14). The orbitoidiform genus *Setia*, with type species *Lepidorbitoides tibetica* Douvillé from the Thanetian of Tibet, was introduced by Ferrández-Cañadell (2002), who demonstrated that its architecture differs from that of the related and largely coeval genus *Orbitosiphon* Rao; both genera are restricted to Tibet, Pakistan, and India. Unfortunately, the name *Setia* was preoccupied by *Setia* Adams and Adams (Gastropoda: Rissoiidae), a circumstance of which its author was not aware at that time (Carles Ferrández-Cañadell, personal communication, 2010). Later, Matsumaru and Jauhri (2003) established the orbitoidiform foraminiferal genus *Lakadongia* from the Thanetian of Meghalaya, with type species *Lakadongia indica* Matsumaru and Jauhri. In turn, Ferrández-Cañadell (2004) demonstrated *L. indica* to be a junior synonym of “*Setia*” *tibetica* Douvillé. Finally, unaware of Matsumaru and Jauhri (2003) and Ferrández-Cañadell (2004), Özdikmen (2009) recognized that the name *Setia* Ferrández-Cañadell, 2002 is preoccupied by *Setia* Adams and Adams and proposed the replacement name *Novosetia*. Notwithstanding the issue of the nomenclatural unavailability of the electronic publication in which it was published (Huber, 2007; ICZN, 2012), the genus-group name *Novosetia* Özdikmen is also invalid because there is an earlier available senior synonym, i.e., *Lakadongia* Matsumaru and Jauhri. This is in accordance with the Principle of Priority, as set forth by the ICZN (1999: Art. 23): if a scientific name is found to be unavailable or invalid, it must be replaced by the next oldest available name among its synonyms. Thus, the valid name for *Setia* Ferrández-Cañadell is *Lakadongia* Matsumaru and Jauhri. The genus *Lakadongia* therefore includes two species, *L. primitiva* (Ferrández-Cañadell, 2002) from the Hangu Formation, and the stratigraphically higher *Lakadongia tibetica* Douvillé from the Lockhart Limestone in the Salt Range in Pakistan. As of yet, this is the only locality where these Paleocene orbitoidiform foraminifera were studied in de-

tail and the evolution of both genera has been recorded (Ferrández-Cañadell, 2002). The Lockhart Limestone is generally considered upper Paleocene, although a firm shallow benthic zonation of the formation has not been proposed yet. Thus, the stratigraphic distribution of *Lakadongia* and *Orbitosiphon* and their species in the Lockhart Limestone are not well constrained in terms of SBZ. Our data from the Lakadong Limestone suggest that *Lakadongia* extends from SBZ 3 to 4, although it is rare in SBZ 4. This, however, may be due to facies change recorded by the prevalence of orthophragminids in the upper part of MQS. Due to lack of information for the embryonic stage of the genus, no species attribution was made for the specimens in the lower part of the section. Specimens of *Lakadongia* from the middle part of the MQS with two “first embryonic chambers” are confidently assigned to *L. tibetica* (Fig. 14.14–17). *Orbitosiphon* is poorly known from the MQS and only a few tangential sections are available (Fig. 14.18–21); thus its stratigraphic range cannot be precisely established.

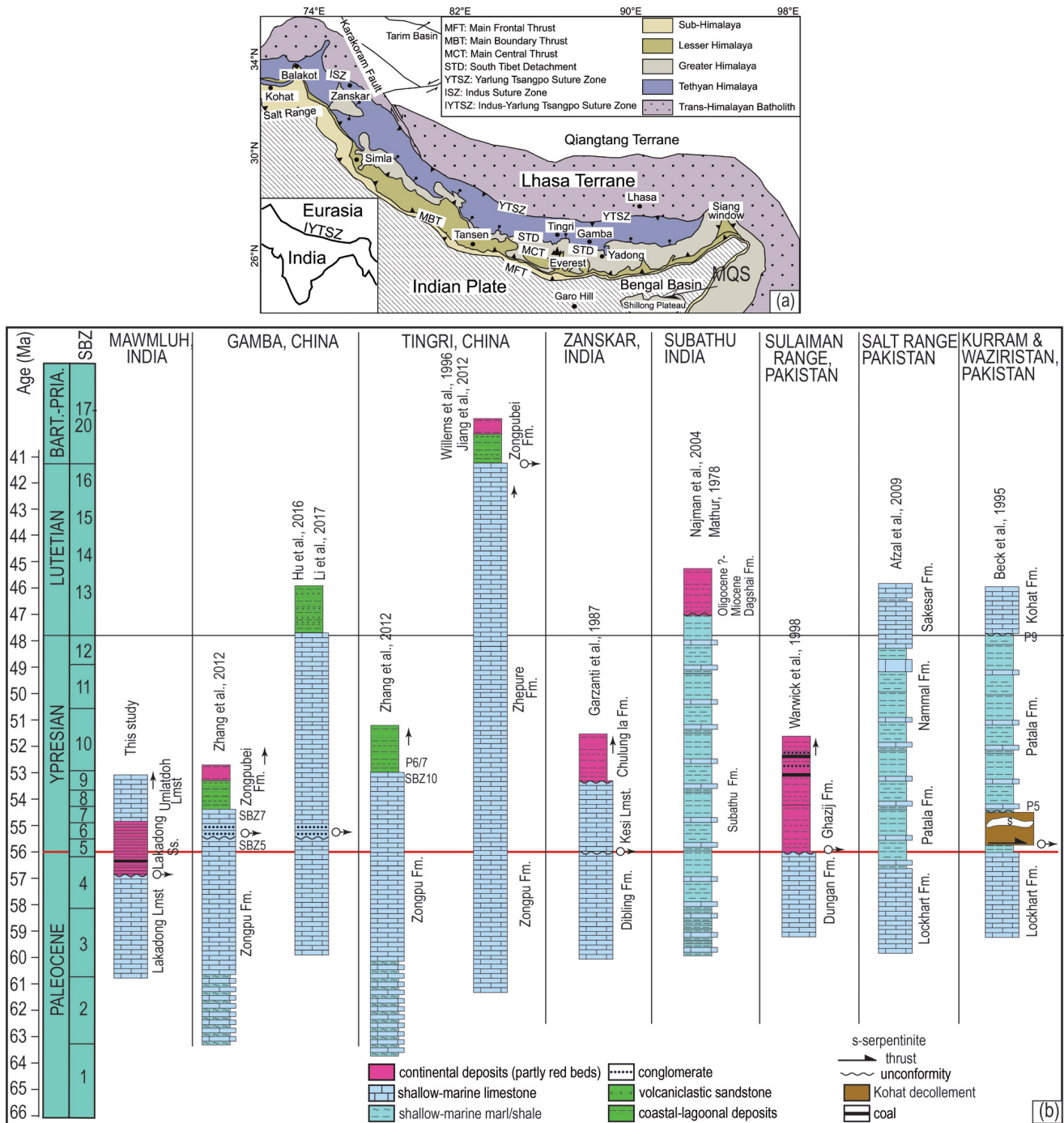
## 8 Significance of the transition from a marine to continental depositional setting in MQS

The late Paleocene to early Eocene corresponds to widespread shallow-marine sedimentation (mainly carbonates) along the northern margin of the Indian plate. Apart from other geological tools, stratigraphic development of the Paleogene sequences on the Indian craton was used as a tool to pinpoint the onset of the collision of the Indian and Asian plates (see Hu et al., 2016, for a synthesis and references therein). These deposits were investigated from Tethyan Himalayas, e.g., the Dibling and Zongpu formations (Garzanti et al., 1987; Green et al., 2008; Zhang et al., 2013; Jiang et al., 2015; Hu et al., 2016), and from the foreland basins in the sub-Himalayas, e.g., the Lockhart Limestone and Dungan Formation in the Salt Range and Sulaiman Range in Pakistan, and the Subathu and Dibling formations in northwest India (Najman et al., 2004; Afzal et al., 2011; Zhang et al., 2012) (Fig. 15). The cessation of the (shallow) marine sedimentation in the shelf and transition to continental setting, deposition of a laterally widespread conglomerate bed within the shallow-marine carbonates marking a break in sedimentation, and shoaling of the outer shelf deposits at or close to the Paleocene–Eocene boundary were commonly linked to the flexural uplift of the passive margin, marking the onset of the collision of the Indian and Eurasian plates (Garzanti et al., 1987; Zhang et al., 2012). In addition, thrusting of accretionary prism and trench complex over the Paleocene passive margin deposits was interpreted to hint the early sign for the onset of a collision (Beck et al., 1995). Nevertheless, a variety of ages ranging from Late Cretaceous to Oligocene–Miocene were assigned to the India–Asia collision based upon the various other criteria and hypotheses (see Hu et al., 2016, and references therein). The Paleocene–Eocene sec-

tions from the Shillong Plateau, which corresponds to the most eastern part of the foreland, however, were not taken into consideration in these reconstructions. Our data from Mawmluh show a sharp facies change from shallow-marine carbonates (Lakadong Limestone) to coal-bearing continental sandstones (the Lakadong sandstone) within SBZ 4. This corresponds to the oldest record for the cessation of marine carbonate sedimentation among the reported passive continental margin deposits (Fig. 15). Lakadong sandstone, ca. 25–250 m thick, consists of arkosic sandstone with thin carbonaceous shale and coal seams and is interpreted to have deposited in estuarine and lagoonal environments (Singh and Singh, 2000). Prasad et al. (2006) recorded the Paleocene–Eocene Thermal Maximum within the Lakadong sandstone and considered a significant part of the unit to be of Thanetian age. Our interpretation is that the drastic facies change in the MQS from a marine to continental setting within SBZ 4 corresponds to the oldest record for the cessation of the carbonate deposition along the passive margin. This was previously reported to be SBZ 6, which corresponds to a conglomerate horizon within the carbonates in the Gamba section in the Tethyan Himalayas (Zhang et al., 2012; Li et al., 2017).

## 9 Discussion and conclusions

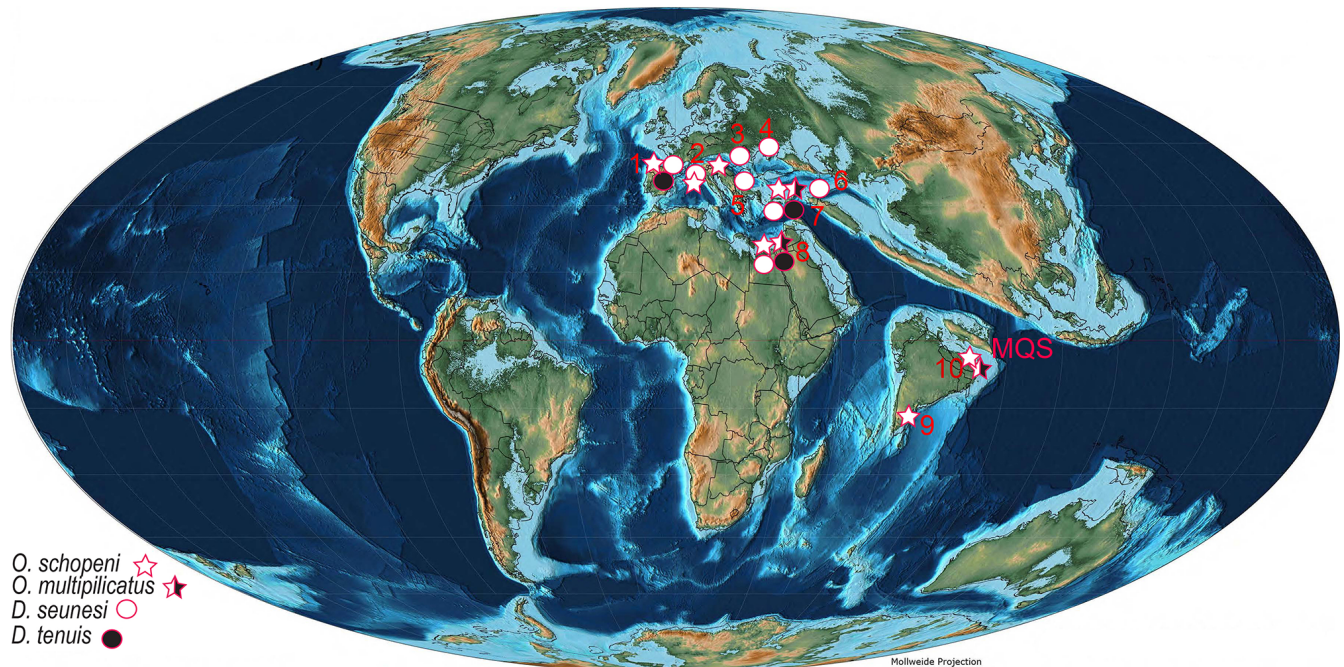
The Lakadong Limestone, a ca. 36 m thick shallow-marine limestone–dolomite unit with fine-clastic intercalations in MQS, can be referred to the shallow benthic zones SBZ 3 and 4, based on the presence of alveolinids, miscellaneous, rotaliids, and some orbitoidiform taxa, the latter group being endemic to the eastern Tethys. The coralline and dasycladalean algae are the main floral elements. The LBF and associated fauna and flora suggest a general deepening up-section from an inner to middle shelf depositional setting. Orthophragminids, rare in the lower and middle and very common in the upper part of the MQS, are subdivided into two lineages of the genus *Orbitoclypeus* Silvestri, *O. schopeni* (Checchia-Rispoli), and *O. multiplicatus* (Gümbel). The distinction of both species externally is unfeasible, due to similar test features, whereas in equatorial sections both species are differentiated based on the embryonic configuration, embryo size, and features of equatorial chambers. *Orbitoclypeus schopeni* is represented by the phylogenetically most primitive subspecies, *O. schopeni ramaraoi*, in the lower part of the section and by a transitional developmental stage of *O. schopeni ramaraoi* and *O. schopeni neumanna* in the upper part. *Orbitoclypeus multiplicatus*, however, represents a transitional stage between *O. multiplicatus haymanaensis* and *O. multiplicatus multiplicatus*. Comparing the embryo size of both species in the section with those of the specimens from the coeval taxa from the western Tethys, we infer that the embryo of both taxa is slightly larger in the eastern Tethys. *Orbitoclypeus multiplicatus* is recorded here for the first time from the eastern Tethys and its ge-



**Figure 15.** Stratigraphic columns of selected areas showing the correlation of Paleocene–early Eocene shallow marine sections in the Himalayan foreland basin in China, India, and Pakistan. A break in the sedimentation across the Paleocene–Eocene boundary is marked by an arrow. The map of Himalaya orogeny is from Jiang et al. (2015).

ographic distribution is extended from eastern Europe and North Africa to northern India (Fig. 16). The absence of *Discocyclina*, a common late Paleocene orthophragminid genus in the western Tethys, from the Paleocene Himalayan foreland basins and southern India, is significant for the eval-

uation of the Eocene development of eastern Tethyan orthophragminids. The stratigraphically oldest *Discocyclina* assemblage in the Indian subcontinent has been recorded from the lower Eocene succession of the Patala Formation in Thal in Pakistan and is represented by *Discocyclina*



**Figure 16.** Distribution of Tethyan late Paleocene orthophragminids on late Paleocene–early Eocene paleogeographic base map (updated from Özcan et al., 2014). 1: Aquitaine Basin (France): Schlumberger (1903), Douvillé (1922), Neumann (1958), and Less (1998). 2: Adriatic Carbonate Platform (Slovenia): Drobne et al. (2012). 3: western Carpathians (Slovakia): Samuel et al. (1972). 4: central and eastern Crimea: Zernetskii (1977), and Zakrevskaya (2007). 5: Bulgaria: Less et al. (2007). 6: Armenia: Grigoryan (1986). 7: Haymana Basin (Turkey): Özcan et al. (2001). 8: Galala (Egypt): Özcan et al. (2014). 9: southern India: Samanta (1967). 10: Meghalaya (NE India).

*ranikotensis*, *D. archiaci*, *D. dispansa*, and *D. aff. fortisi*. Both *Discocyclus* *ranikotensis* and *D. aff. fortisi* are endemic to the Indian subcontinent and the embryonic size of *D. archiaci* also appears to be slightly larger than that of the western Tethyan *D. archiaci* (Özcan et al., 2015). Combining the orthophragminid records from Meghalaya, Pondicherry, in SE India and the lower Eocene Patana Formation in Thal, Pakistan, and taking into account the published evidence on Paleocene LBF assemblages from the southern Asian and Indian margins, we maintain that *Orbitoclypeus* was the sole orthophragminid genus in the Paleocene of eastern Tethys and *Discocyclus* only appeared in early Eocene times with predominant endemic taxa confined to the Indian subcontinent.

**Data availability.** The material can be accessed at the Geology Department of İstanbul Technical University.

**Competing interests.** The authors declare that they have no conflict of interest.

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